Detrital Zircon Provenance of Upper Cambrian-Permian Strata and Tectonic Evolution of the Ellsworth Mountains, West Antarctica

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Abstract

Detrital zircons from the upper Cambrian-Devonian sandstones (Crashsite Group; n=485) and Carboniferous tillite (Whiteout Conglomerate; n=81) of the Ellsworth Mountains, Antarctica record a steady supply of Neoproterozoic ("Pan-African") orogeny (~550-600 Ma), Grenville (~1000 Ma) and Neoproterozoic (~3000-3500 Ma) zircons into the northern marginal basin of Gondwana. The overlying Permian *Glossopteris*-bearing Polarstar Formation shales (n=85) have the same zircon provenance as underlying units but also include a dominance of depositional-age (263 Ma) euhedral zircons which are interpreted to be of local, volcanic arc origin. Modeling of detrital zircon provenance suggests that source areas were present in Pan-African and Laurentian crust throughout the Paleozoic. We also report calcite twinning strain results (12 strain analyses; n=398 twins) for the Cambrian Minaret Fm. in the Heritage range which is predominantly a layer-parallel shortening strain in the direction (WSW-ENE) of Permian Gondwanide orogen thrust transport. There is a secondary, sub-vertical twinning strain overprint. The initiation of localized lower-middle Cambrian

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4 rifting (Heritage Group deposition) in Grenville-aged crust as Gondwana
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6 amalgamated and the subsequent Jurassic counterclockwise rotation of the
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8 Ellsworth-Whitmore terrane out of the Permian Gondwanide belt into central
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10 Antarctica each remain tectonic curiosities.
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13 **Introduction**

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15 The Ellsworth Mountains lie in the interior of West Antarctica, are 350 by
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17 80 km in dimension, and are structurally perpendicular to adjacent crustal
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19 fragments (Fig. 1). They are divided into the northern Sentinel range and the
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21 lower, southern Heritage range. The Ellsworth Mountains are the highest
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23 standing feature in Antarctica with the Vinson Massif reaching 4892 m. These
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25 mountains are part of the Ellsworth-Whitmore terrane (EWT; 720,000 km²), which
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27 are tectonically isolated from the remainder of the continent (Anderson et al. 1962;
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29 Craddock, 1966, 1972; Schopf, 1969; Dalziel and Elliot, 1982; Maslanyi and Storey,
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31 1990; Curtis and Storey, 1996; Figure 1). The EWT is located in central Antarctica
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33 and is composed of Grenville-aged crust (Pankhurst and Millar, 1987; Flowerdew
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35 et al. 2007; Craddock et al. 2008; 2016) and was the site, on the southern margin
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37 of Gondwana, for deposition of 13,000 m of conformable Cambrian-Permian
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39 sediments including the classic Gondwana sequence: upper Cambrian-Devonian
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41 sands (Crashsite Group), Carboniferous tillites (Whiteout Conglomerate) and
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43 Permian near-shore, fossiliferous shales (Polarstar Formation; Webers et al. 1992).
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45 The lower half of this stratigraphic sequence (~7000 m) is the middle-upper
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47 Cambrian Heritage Group which is a volcanoclastic sequence deposited
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49 unconformably on rifted Grenville-aged crust that was both in-board of the
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51 convergent Gondwana margin and unaffected by the proximal Ordovician Ross
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53 orogeny (Curtis and Lomas, 1998; Curtis et al. 1999a, b; Figures 2 and 3). There is
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4 now detrital zircon data for the upper Cambrian-Permian part of the Ellsworth
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6 Mountains section and no strain data.
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11 One goal of this study was to use detrital zircon populations in the
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13 Ellsworth Mountains stratigraphic section to better resolve the location of the
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15 EWT during Paleozoic sedimentation, by comparing the detrital zircon age
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17 spectra obtained with the known ages of possible surrounding crustal blocks in
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19 Gondwana. In addition, we seek to better constrain the location of the EWT
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21 Grenville crust as part of diverging Rodinia (Moores, 1991; Dalziel, 1991, 1992,
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23 1997; Goodge et al., 2008, 2010, 2012) as Cambrian sedimentation commenced.
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25 We report U/Pb detrital zircon results from the Cambro-Devonian Crashsite
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27 Group (northern Heritage Range and Vinson Massif profile; 6 samples), the
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29 Carboniferous Whiteout Conglomerate (tillite; 1 sample) and the Permian
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31 Polarstar Formation (1 sample; see Elliot et al. 2016) and compare these results
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33 with Flowerdew et al. (2007; 2 samples, upper Heritage Group; 1 sample of the
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35 upper Crashsite Group) for the Ellsworth stratigraphic section as part of the
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37 Grenville-cored southern margin of Gondwana. We also report calcite twinning
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39 strain results from the Cambrian Minaret Fm. in the Heritage Range and discuss
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41 these results relative to the Gondwanide orogeny in the EWT.
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51 **Geologic Setting**

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53 Tectonically, the Ellsworth Mountains are situated between the East Antarctic
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55 craton and the accreted terranes of West Antarctica, namely the Antarctic Peninsula,
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57 Thurston Island and Marie Byrd Land (Dalziel and Elliot, 1982; Dalziel et al. 1987;
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59 Curtis and Storey, 1996). The Cape Fold Belt of Africa (DuToit, 1937; Halbach, 1982),
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the Sierra de la Ventana Mountains in Argentina (Von Gosen et al. 1987; Cobbold et al. 1991), the Falkland archipelago and the Ellsworth Mountains (Craddock, 1983; Webers et al. 1992) were all segments of one late Proterozoic-Paleozoic margin deformed in the early Permo-Triassic Gondwanide orogen (De Wit and Ransome, 1992). The preferred Gondwanide location of the EWT is $\sim 90^\circ$ clockwise from its present location (Watts and Brammall, 1981; Randall and Mac Niocaill, 2004; Cambrian paleopole solutions) in proximity to the Pensacola Mountains and the Argentina Range that lie in the Weddell Sea sector of the Transantarctic Mountains, a location that aligns all structural elements (Curtis, 1997, 1998, 2001). When the EWT diverged from Gondwana, the process included a bimodal igneous suite including pervasive Jurassic mafic intrusions (e.g., Dufek massif; 180 Ma; Minor and Mukasa, 1997) and extrusives (e.g., the Ferrar dolerite; 182.779 $\pm$ 0.033 Ma; Burgess et al. 2014) as part of the Tasman-Karoo LIP (Craddock, 1972; Storey et al., 1988; Kyle, 2000; Craddock et al., 2008; 2016). These Jurassic mafic rocks are slightly older than the intrusion ages of granites in the EWT (173-177 Ma; Craddock, 1972; Storey et al. 1988; Craddock et al. 2016). Thus, granitic intrusion occurred *after* rotation of the EWT into its final position relative to the Weddell Sea (Grunow et al. 1987; Grunow, 1993; Elliot and Fleming, 2000). It remains unclear how and when the EWT moved to its current location in central Antarctica as Mesozoic and Cenozoic basin fill in the evolving, adjacent Weddell Sea is apparently undeformed (Huebscher et al. 1996; Grunow, 1993). Subsequent uplift of the EWT, as documented by the fission track study by Fitzgerald and Stump (1991) using the Devonian Crashsite Quartzite profile in the Sentinel Range, documents 4 km of Cretaceous (100 Ma) exhumation which led Dalziel (2008) to propose that the Ellsworth Mountains have long been a central glacial buttress (total relief = 7 km) thereby stabilizing Tertiary ice volumes in East and West Antarctica. POLENET is a

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4 multi-national consortium undertaking a continent-wide GPS and seismic array to
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6 document active tectonism across Antarctica (Dalziel, 2008).
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11 The Ellsworth Mountains are comprised dominantly of a ~13,000 m basal
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13 middle Cambrian to Permian apparently conformable sedimentary sequence
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15 (Webers et al. 1992; Curtis and Lomas, 1999; Curtis et al. 1999a, b; Fig. 3). It
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17 contains two groups, the Heritage (Lower Cambrian to Upper Cambrian;
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19 marbles, argillites, quartzites, conglomerates with some volcanics) and the
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21 Crashsite Groups (Upper Cambrian to Devonian, dominantly quartzites). Other
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23 fossiliferous sections such as the middle Cambrian Springer Peak coquina (70
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25 new species; Webers et al. 1992) as well as a variety of dated igneous intrusions
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27 and igneous clasts better refine the stratigraphic column (Flowerdew et al. 2007;
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29 Figure 3). Clastic, carbonate and volcanoclastic sediment of presumed Cambrian
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31 age are known in widely separated locales around the EWT and likely correlate
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33 with the Heritage section and thereby bear on the early Cambrian rifting of the
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35 EWT (Storey and MacDonald, 1987). The Heritage and Crashsite Groups are
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37 separated by a series of transitional beds (Webers et al. 1992; Curtis, 2001) that
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39 had been interpreted as subtle evidence for the Cambro-Ordovician Ross
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41 orogeny in the EWT (Goldstrand et al., 1994; Rees et al., 1995; Rees and
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43 Duebendorfer, 1996). However, these transitional beds are interpreted by later
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45 workers as local unconformities without regional significance notably as there is
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47 structural continuity across this boundary, and thus the Ross Orogeny, which is
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49 so prelevant in the Transantarctic Mountains (e.g., Stump, 1992), is concluded to
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51 be absent in the Ellsworth Mountains by Curtis (2001). Two younger formations,
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53 the Permo-Carboniferous Whiteout Conglomerate (marine and terrestrial tillites)
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4 and the Permian Polarstar Formation (argillite and sandstone) complete the
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6 upper section. Craddock et al. (1965) first described *Glossopteris* flora in the
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8 Polarstar Formation at the top of the Ellsworth stratigraphic section thereby
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10 connecting these mountains to the Gondwana (Karoo) basin and Gondwanide
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12 orogeny (Schopf, 1969; Craddock, 1977).
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18 The Ellsworth Mountains are a NNW-plunging anticlinorium exposing
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20 Cambrian sediments and metavolcanics in the southeast and the Permian
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22 Polarstar Formation in the northwest as part of the Gondwanide orogen thrust
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24 belt (Craddock, 1977; Figure 2). Thrusts dip to the WSW and hangingwall
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26 motions are up and to the ENE (Sporli et al. 1992; Craddock et al. 1992; Curtis,
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28 2001) and a layer-parallel shortening strain is present in the Cambrian Minaret
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30 carbonates (Craddock et al. 1997). Folds are overturned to the ENE and an axial
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32 planar cleavage is present; foliation-bound kinematics also indicate top-to-the-
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34 ENE motion (Curtis, 1997, 1998, 2001) in rocks that reached greenschist facies
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36 metamorphic grade (Bauer, 1992). The Cambrian Minaret Formation carbonates
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38 host a 3-phase carbonate breccia body formation that was contemporaneous with
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40 the Gondwanide orogen and is seemingly unique to this thrust belt (Sporli et al.
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42 1992; Craddock et al. 2008). Post-Gondwanide dextral deformation, parallel to
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44 the overall strike, is also reported (e.g., Dolence fault; Craddock, 1980; Craddock
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46 et al. 1986; Curtis, 2001), perhaps related to Mesozoic rotation and subsequent
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48 translation of the Ellsworth-Whitmore terrane.
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58 Ellsworth Mountains Stratigraphy

59 *The Heritage Group*

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4 The southern Heritage Range is composed of ~7000 m of heterogeneous
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6 clastic, volcanoclastic and fossiliferous carbonate sediments of the Cambrian
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8 Heritage Group. Some parts of the Heritage Group are fault-bounded and the
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10 stratigraphy is locally discontinuous and with local unconformable surfaces
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12 (Webers et al. 1992; Curtis et al. 1999; Curtis, 2001). Radiometric ages and detrital
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14 zircon spectra within the Cambrian section by Flowerdew et al. (2007) have
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16 refined the stratigraphic column initially proposed by Craddock (1969; Figure 3).
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22 *Minaret Formation*

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25 The Minaret Fm. is a shallow marine deposit of upper Cambrian age. The
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27 unit is 600-900 m thick and is dominantly a carbonate with oolites, oncolites, flat-
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29 pebble conglomerates, ripples and cross beds. Upper Cambrian fossils are
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31 numerous and the Minaret Fm. was deposited on the Frazier Ridge-Springer
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33 Peak- Liberty Hills Fm. (Fig. 3; Buggisch and Webers, 1992; Buggisch et al. 1992).
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35 The Minaret Fm. provides a beautiful carbonate for calcite strain analysis
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37 (Methods in Appendix 1) and is the carbonate host for the synorogenic
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39 monomineralic 3-phase calcite breccia bodies (Sporli et al. 1992; Craddock et al.
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41 2008). The Heritage (see above)-Minaret section correlate with the Gamtoos-
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43 Kango inliers in southern Africa (Miller et al. 2016).
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50 *Crashsite Group*

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53 The overlying Crashsite Group is ~3000 m in thickness and the base may
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55 be Cambrian, Silurian or Ordovician but appears to be conformable with the late
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57 Cambrian underlying Heritage Group (Sporli, 1992; “transition beds” of Curtis,
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59 2001). Paleocurrent and index fossil data are sparse in these shallow marine
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4 sands and rare, interbedded shales and conglomeratic layers. The relief of the
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6 Sentinel Range (4892 m) is the result of the enormous thickness of resistant
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8 Crashsite quartzites that are folded, overturned and repeated (Craddock et al.
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10 1992). Crashsite Group quartzites are common in the Heritage Range and, since
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12 the entire Ellsworth Mountains are north-plunging, correlations with the
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14 overlying Crashsite Group quartzites in the high-standing Sentinel Range have
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16 proven challenging (Fig. 5). The Crashsite Group correlates with the Witteberg-
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18 Bokkeveld and Table Mtn. Fms. in the Cape Mountains, the Ventana and
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20 Curamalal Fms. in the Ventana Mountains, and the Port Stanley-Fox Bay-Port
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22 Stephens Fms. in the Falkland Islands.
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29 *Whiteout Conglomerate*

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32 Exposures of the Whiteout Conglomerate in the Ellsworth Mountains
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34 include the massive, folded diamictite in the northern Sentinel Range and the
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36 thinly-bedded, interbedded diamictite-tillite in the southern Meyers Hills of the
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38 Heritage Range (Matsch and Ojakangas, 1992). Exposures in the Meyers Hills
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40 included mixed diamictite-tillite zones with boulder pavements (the grounding
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42 line) and abundant glacially striated clasts all indicating the ice flowed from the
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44 southern Meyers Hills toward the northerly open ocean (Sentinel Range) in the
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46 Carboniferous. The Whiteout Conglomerate correlates with the Dwyka Fm. in S.
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48 Africa, the Sauce Grande Fm. in Argentina and the Fitzroy Fm. in the Falkland
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57 *Polarstar Formation*

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Craddock et al. (1965) first described Polarstar Formation *Glossopteris* flora in central Antarctica from the top of the Ellsworth stratigraphic section thereby connecting these mountains to the Gondwana basin and Gondwanide orogeny (Schopf, 1969; Craddock, 1977). The Polarstar Formation is >1000 m and composed of a lower argillite, sandy argillite and upper coal measures with paleocurrents (n=119) that dominantly flowed toward the northwest, away from Gondwana (Collinson et al. 1992). The Polarstar is weakly metamorphosed but intensely folded (Castle and Craddock, 1975) and our sample is from the lower argillite unit collected near Polarstar Peak. Elliot et al. (2014) have recently reported detrital zircon and zircon ash crystallization results for the Polarstar Formation and equivalent units nearby. The Polarstar Fm. correlates with the marine Eccu and terrestrial Beaufort Group in the Cape-Karoo system, the Pilahuinco Fm. in the Ventana Mountains and the Black Rock Slates in the Falkland Islands.

Sampling and Results

We report here the details of the analysis of detrital zircon populations for eight samples from the northern Heritage Range to the northern end of the Sentinel Range in the Ellsworth Mountains (Figures 1, 2 and 3; U-Pb methods in Appendix 1). Webers et al. (1992) provides a compendium about the Ellsworth Mountains, including the exploration history in the Preface, and a geologic map (Craddock et al. 1986) that is simplified in Fig. 2. A stratigraphic column, after Webers et al. (1992) and Flowerdew et al. (2007) is found in Figure 3. Detrital zircon relative probability results, including three samples from Flowerdew et al. (2007), are presented in Figure 4, and the U-Pb age data are summarized in Table

1 and reported in full in Appendix 2. Calcite strain sample sites are located on Fig. 2, stereoplots in Fig. 5, and data are presented in Table 2. Field structural relations are presented in Figures 6-8.

Detrital Zircon Spectra

Crashsite Group Quartzites

Seven samples were collected, three from the northern Heritage Range (HR-6, HR-37 and HBJ) and four from a traverse up the Vinson Massif (HBO, HAS, HAT, HBD; Table 1). All but sample HBO had robust zircon yields (Appendix 2) and the U-Pb age results are presented in Figure 4. All six results (n=485, plus 91 U-Pb ages from Flowerdew et al. 2007) are fairly consistent with spectral peaks at 550-600 and 1100 Ma with small numbers of older zircons. The youngest zircons are 486, 504, 505, 511, 484 and 484, from bottom to top, are Cambro-Ordovician ages which do not better constrain a Crashsite depositional age. We also dated eleven grains between 3000 and 3452 Ma.

Whiteout Conglomerate

Matsch and Ojakangas (1992) report that the 1000 m thick Whiteout is populated by quartzite (66%) and granite clasts (17%) and petrographic analysis reveals a variety of feldspars and garnet. Samples from both the northern Sentinel Range and Meyers Hills have significant pyrope garnets in their heavy mineral splits as does the Fitzroy Formation in the Falkland Islands and the Dwyka Formation in southern Africa (Craddock et al. 2008). The detrital zircons (n=81) from the northern Sentinel Range Whiteout Conglomerate include a primary U-Pb age population at 550 Ma and a few lesser peaks at 1100, 1800 and

2700 Ma (Fig. 4). The youngest zircon age is 519 Ma. The oldest zircon age is 3569 Ma.

Polarstar Formation

Zircon grains from the Polarstar Formation exhibit two morphological populations. About half of the zircon crystals are euhedral and unabraded (Fig. 4) and the other half of the zircon crystals are usually rounded, abraded zircons (Fig. 1, n=43). The euhedral zircons are all young and are presumed to be ashfall zircons from a proximal magmatic event; possibly arc-related magmatism (n=42; see Fildani et al. 2010 and McKay et al. 2015 for a correlation to Permian Karoo sediment ash fall zircons). A weighted mean age of the young zircons was calculated and interpreted to reflect a depositional age of 263.4 ± 1.4 Ma (95% confidence level; MSWD of 1.6; Fig. 4 inset). This depositional age is consistent with the results of Elliot et al. (2014) who report maximum depositional ages of 270 and 260 Ma, respectively as well as the crystallization ages of interbedded ash deposits (258 and 262 Ma). The rounded zircons give age distributions with peaks at 550, 800 and 1200 Ma (Fig. 4); the oldest zircon is 3163 Ma. The U-Pb zircon analyses that are older than Permian yield a similar distribution (age populations and peaks) to the older part of the section (Crashsite Group).

Structural Geology & Calcite Twinning Strains

Folds in the southern Heritage Range are periclinal and fold hinges dip to the WSW (verge to the ENE) and generally contain an axial planar cleavage. The Minaret Fm. limestones are marbles in places and can be mylonitic with top-to-

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4 the-NE porphyroclasts and porphyroblasts (Fig. 6; Curtis, 1997, 2001). Strike-slip
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6 faults also crosscut the Gondwanide folds and these fault planes (Fig. 6) are
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8 occasionally filled with calcite breccia material. The breccia bodies had a three-
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10 stage genesis, with the older breccias containing cleaved upper Cambrian
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12 Minaret limestone clasts supported by calcite, whereas the younger breccias are
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14 nearly clast-free and composed entirely of matrix calcite (Fig. 7). Breccia clasts,
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16 calcite matrix and detrital matrix samples are entirely composed of calcite and
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18 stable isotopes (C, O) and fluid inclusions (140°C homogenization temperature)
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20 suggest that the breccias formed as part of a closed geochemical system within
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22 the Minaret Fm. at considerable depth (~5000 m; Craddock et al. 2008). Breccia
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24 bodies are offset by Gondwanide orogen thrusts (Fig. 8a) and are therefore
25
26 synorogenic features; mechanical twins are present in breccia body matrix calcite
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28 but no oriented samples were collected. Breccia bodies are sheared (reverse and
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30 sinistral motion) along the post-Gondwanide Dolence fault (Figs. 2, 8b) that is
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32 parallel to the structural fabric of the Ellsworth Mountains.
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39 The deformation of the Marble, Independence and Patriot Hills in the
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41 southern Heritage Range is consistent with Gondwanide orogen deformation
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43 throughout the Ellsworth Mountains (Sporli and Craddock, 1992a,b). Eight
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45 oriented carbonate samples were collected in 1979-80, which resulted in 12 calcite
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47 twinning strain results (Table 2, Fig. 5). Strain results for 6 limestones record a
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49 layer-parallel shortening strain in the direction of inferred Gondwanide thrust
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51 transport, or normal to fold axes (WSW-ENE). Two vertical calcite veins record
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53 horizontal shortening parallel to the Gondwanide thrust transport direction.
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55 Strain overprints (high NEV %) are evident in 3 limestones and 1 vein, and in
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57 each case a sub-vertical shortening strain was imposed on the layer-parallel
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4 fabric. Differential stresses responsible for twinning and the resultant strain
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6 magnitudes are consistent with other thin-skinned thrust belts (Table 2).
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10 11 **Discussion** 12

13 *Depositional History and Provenance* 14

15 The Ellsworth Mountains stratigraphic section is unique as nearly half of the
16 conformable 13,000 m section is composed of heterogeneous clastic and volcanoclastic
17 Cambrian sediments and local intrusions that rest on Grenville basement and were
18 deposited as the margin rifted in the Cambrian (Curtis, 1999). The Ellsworth-
19 Whitmore terrane avoided the regional Pan African orogeny (550-600 Ma) and
20 Cambro-Ordovician deposition was unaffected by the proximal Ordovician Ross
21 orogeny (~530-500 Ma; Paulsen et al. 2007). Gondwana reconstructions (Watts and
22 Brammall, 1981; Grunow et al., 1987; Lawver et al. 1991; Randall and Mac Niocaill,
23 2004) locate the Ellsworth-Whitmore terrane in the Natal embayment adjacent to S.
24 Africa, the Falkland Islands, the Coats Land terrane, and along the Transantarctic
25 Mountains near the Grenville crust in the Grunehogna terrane (Jacobs et al. 2003 a,b;
26 Loewy et al. 2011) thereby discarding the equatorial location of the EWT in the
27 Cambrian (Randall et al. 2000). Cambrian sedimentation and rift-related volcanics are
28 also preserved along the Gondwana margin in southern Africa (Kango, Kaaimans and
29 Gomtoos inliers; Miller et al. 2016), with local unconformable surfaces, before the onset
30 of late Cambrian shallow marine sandstone deposition (Curtis, 1999a). Cambrian mafic
31 dikes in the Falkland Islands indicate contemporaneous crustal extension (Curtis et al.
32 1999b). Storey and MacDonald (1987) report ~100 m of flat-lying volcanoclastic
33 sediments in the southern EWT near the north side of the Thiel Mountains, ~400 m of
34 vertical carbonates in the Nash Hills, and ~120 m of flat-lying red sandstones at Mt.
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4 Johns (Figure 1). These are all presumed to be Cambrian in age and may correlate with
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6 the Heritage Group. What was adjacent to the southern margin of Gondwana at the
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8 end of the Proterozoic that rifted away and commenced Cambrian sedimentation on
9
10 Grenville crust?
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16 Paleocurrents are not common in the Cambrian Heritage Group sediments
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18 in the Ellsworth sequence and perhaps this is expected for volcanoclastic
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20 sediments in a narrow (~100 x 500 km) rift basin. The overlying Gondwana
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22 sequence is generally a shallow marine sequence and the Cambro-Devonian
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24 sandstones (Tankard and Barwis, 1983; Hiller and Taylor, 1992) with poorly
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26 organized sediment transport (Sporli et al. 1992) and intensely folded (i.e.,
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28 nappes) making interpretations difficult. Carboniferous tillites preserve well-
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30 defined ice flow indicators from central Africa and Antarctica (Visser, 1987;
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32 Matsch and Ojakangas, 1992). Permian *Glossopteris*-bearing Polarstar Formation
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34 (Curtis and Hyam, 1998; Collinson et al. 1992) and equivalent units in the Karoo
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36 basin preserve a mix of paleocurrent data (Cole et al. 1998; Andersson et al.
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38 2006). The Frasier Ridge-Crashsite Group detrital zircons all record a steady
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40 stream of Pan African (550-600 Ma) and Grenville (~1100 Ma) aged zircons into
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42 the Gondwana basin. The Whiteout Conglomerate (tillite) has the same detrital
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44 zircon age spectra with small age peaks at ~2000, ~2800 and ~3600 Ma, similar to
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46 the detrital zircon age spectra in the Fitzroy, Dwyka and Sauce Grande tillites
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48 (Craddock, 2011). The Whiteout, Fitzroy, Dwyka and Sauce Grande Fm. tillites
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50 also contain healthy populations of pyrope garnets (Craddock et al. 2008;
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52 Craddock and Thomas, 2010). The Polarstar Formation is dominated by arc-
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54 related Permian ashfall zircons (263 Ma; Fig. 4; see Millar et al. 2001, 2002; Fildani
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4 et al. 2010; Elliot et al. 2014; McKay et al. 2015) and a smaller population of Pan
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6 African and Grenville detrital zircons. Only the youngest zircons in the lower
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8 Fraser Ridge Formation (518 Ma) and upper Wyatt Earp Member (375 Ma) of the
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10 Crashsite Group better constrain the depositional ages of these units and are
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12 consistent with the overall stratigraphic sequence. The consistency of youngest
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14 zircon ages in the majority of the Crashsite Group samples may reflect sample
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16 duplicity in a complexly folded and repeated section (Fig. 9).
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23 Deposition on the southern margin of Gondwana started with local
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25 infilling of the Cambrian rift basin (e.g., Heritage Group) followed conformably
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27 by the rest of the Gondwana sequence. As the entire sedimentary sequence is
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29 conformable and largely marine, recycling of zircons was unlikely. The
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31 deposition of the Paleozoic section in the Ellsworth Mountains on Grenville crust
32
33 and in proximity of southern Africa predictably yields both Grenvillian and Pan
34
35 African zircons (Fig. 4). Paleocurrent studies also support a sediment source
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37 from Gondwana toward the basin including the ultramafic pyrope garnets found
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39 in the Carboniferous tillites. Flowerdew et al. (2007) used detrital zircon U-Pb
40
41 geochronology and Hf-isotopic compositions (a mixture of positive and negative
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43 values) to propose four zircon source areas that are not necessarily in agreement
44
45 with paleocurrent indicators. In this study, we have chosen a different approach
46
47 (see Konstantinou et al. 2014) using a ternary plot of detrital zircon ages for the
48
49 entire sample suite (n=775). In this plot we portray the three geologically related
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51 age groups of 550-600 Ma (Pan African group), 950-1350 Ma (Grenville-age
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53 zircons) and a combined mode of 1450-2000 Ma plus 2500-3800 Ma, representing
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55 Laurentian (or Rodinian?) cratonic terranes. As mentioned earlier, few zircons
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4 were observed in the age range of 2000-2500 Ma which is a well-known period of
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6 quiescence of zircon production in Laurentia. The proportions of the three zircon
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8 age modes were calculated for each sample, together with an estimate of the
9
10 standard error for each mode's proportion. These proportions were plotted on a
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12 ternary diagram illustrating the relative zircon age proportions of the three
13
14 groups outlined above. For all of the samples (except the Polarstar Formation
15
16 sample; see earlier discussion), >75% of the zircon data is represented on the
17
18 ternary diagram. This plot helps us outline potential sources for the detrital
19
20 zircons in the EWT samples. The most straight-forward interpretation of these
21
22 detrital zircon signatures is that the zircons were primarily sourced from a
23
24 combination of Pan African and Laurentian crustal sources that contained the
25
26 three age groups described above but lacked a 2000-2500 Ma crystalline source
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28 (Figure 10). Detrital zircon studies of younger, adjacent terranes, the Antarctic
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30 Peninsula, Patagonia and Zealandia, have very different detrital zircon age
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32 spectra, as expected (Barbeau et al. 2009).
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41 Our data suite has 15 zircon ages that are Paleo-Mesoarchean (2800-3600
42
43 Ma; Table 2). The age distribution is as follows: Crashsite Group (2811, 3141,
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45 3211, 3452 Ma [Mt. Twiss Member]; 2976, 2981, 3002, 3018, 3158 Ma [Landmark
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47 Peak Formation]; 2964, 2968, 3024 Ma [Mt. Liptak Formation]; 2893 Ma [Mt.
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49 Wyatt Earp Formation], Whiteout Conglomerate (3569 Ma), and Polarstar
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51 Formation (3163 Ma). Hf isotope data exists for 2893 ($\epsilon\text{Hf} = -4.4$) and 3141 ($\epsilon\text{Hf} = -$
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53 0.9) Ma grains in the Crashsite Group (Flowerdew et al. (2007), and perhaps
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55 these are Laurenitan zircons. Harley and Kelly (2007) have compiled the
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4 complexity of exposed Archean crust in Antarctica (ages of 2460-4000 Ma), data
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6 supported by studies of modern Antarctic glacial tills that source Archean crust
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8 under the modern ice sheet (Goodge et al. 2008). In both cases, the Paleo-
9
10 Mesoarchean detrital zircons in the Ellsworth Paleozoic section (no ϵHf data)
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12 could have been derived from the Nimrod Group in the Transantarctic
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14 Mountains or from central Antarctic crustal sources (Boger, 2011; Veevers and
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16 Saeed, 2011) although this is not supported by limited paleocurrent data. Paleo-
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18 Mesoarchean zircons are known in the Minnesota River valley (MRV) of the
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20 Superior province of southern Laurentia (no ϵHf data; Bickford et al. 2006;
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22 Schmitz et al. 2006) and could have been a primary or recycled source area (no
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24 ϵHf data; Craddock et al. 2013). Antarctica was covered by a polar ice cap for 65
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26 Ma (Lopez-Gamundi, O.R., and Buatois, L.A., 2010) in the Carboniferous which
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28 likely limited much sediment delivery from central Antarctica to this part of the
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30 Gondwana basin.
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40 Goodge et al. (2010) have argued convincingly that East Antarctica and
41
42 Laurentia were sutured together during intrusion of anorogenic granites (~ 1.45
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44 Ga) in both continents thereby supporting the tectonic ("SWEAT") hypothesis of
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46 Moores (1991) and Dalziel (1991, 1992, 1997). Much of Rodinia remained sutured
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48 together by the central Pan African orogeny (600-550 Ma) as a precursor to the
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50 amalgamation of Gondwana (Torsvik et al. 2008). The Grenville crust of the EWT
51
52 fits nicely in the Grenville-Mozambique belt in these end-Proterozoic
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54 reconstructions but was then rifted in the middle Cambrian in a back-arc setting
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56 (Figure 6; Curtis et al. 1999a; Curtis, 2001) before the onset of upper Cambrian-
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4 Permian shallow marine sedimentation. Dalziel (1997) shows the reconstruction
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6 of Rodinia with a continental block containing the EWT as a key element in these
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8 reconstructions linked with Laurentia. The paleomagnetic fit for SWEAT is not
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10 perfect (Torsvik et al. 1996; Van Staal et al. 1998; Curtis, 2001) and the rifting
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12 event at 550 Ma is earlier than Heritage Group deposition although there are
13
14 significant paleobiologic connections between Laurentian and Ellsworth middle
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16 Cambrian trilobites (Jell, 1974; Jago and Webers, 1992) and conodonts (Webers et
17
18 al. 1992). The ancestral mollusc, *Monoplacophera*, is only found at Taylors Falls,
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20 Minnesota (Laurentia) and in the middle Cambrian of the Ellsworth Mountains
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22 (Webers et al. 1992; Figure 7). Proterozoic rhyolites and granophyres (1.1 Ga)
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24 found in the Coats Land terrane also correlate with Keweenaw rift rocks in
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26 southern and central N. America (Loewy et al. 2011; Craddock et al. 2013). If the
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28 Coats Land terrane contains 1.0 Ga igneous rocks equivalent to the Keweenaw
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30 rift system in N. America (see Craddock et al. 2013) perhaps these rift-aged rocks
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32 intrude a fragment of Laurentian crust, an observation supported by the
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34 proximity of the EWT and Coats Land terranes and the Laurentian supply of
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36 detrital zircons we see in the Ellsworth section (Figures 4 and 11). A proximal
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38 zircon source is preferred to a model of across-plate fluvial transport (see
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40 Rainbird, 1992; Craddock et al. 2013), especially if the source area, Laurentia, is
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42 required to move to its N. America-Eur-Africa location at the start of the Taconic
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44 orogeny in the late Ordovician and was not part of Gondwana. Paulsen et al.
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46 (2016) report detrital zircon ages from Ross Supergroup deformed sandstones in
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48 the Wilson, Bowers and Roberston Bay terranes in the North Victorialand (NVL)
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50 area of the Transantarctic Mountains and their age spectra is very similar to the
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52 entire Ellsworth section: age peaks of Pan-African, Grenville and Paleo-

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4 Mesoarchean ages (3566 Ma is their oldest detrital zircon age). We cannot,
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6 however, rule out Archean east Antarctica as a source of these ancient zircons
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8 although the oldest groupings are 3100-3350 Ma (Veevers and Saeed, 2011) and
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10 our oldest detrital zircon in 3569 Ma.
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15 *Deformational History*

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18 The lower-middle Cambrian Heritage Group clastics and volcanoclastics
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20 were deposited on Grenville crust (Millar and Pankhurst, 1987; Craddock et al.
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22 2016) in a localized extensional Ellsworth basin between cratonic east Antarctica,
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24 Africa, India, South America and Laurentia (Figs. 11 and 12) as Gondwana
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26 amalgamated. The Heritage Group is poorly studied (3 detrital zircon samples;
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28 Flowerdew et al. 2007) but the detrital zircon age spectra are consistent with a
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30 provenance with the rest of the younger Ellsworth section (Figs. 4) and the
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32 volcanic rocks are consistent with a localized rifting environment. The Heritage
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34 Group detrital zircon spectra (Pan African, Grenville and Meso-Archean age
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36 peaks) and rift-related volcanics also correlate with the Kango-Kaaiman-
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38 Gomtoos Cambrian inliers in the Cape belt of the same age (Miller et al. 2016)
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40 although this extensional basin formation is separated from the Ellsworth
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42 Heritage extension (Fig. 11).
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51 The Permian Gondwanide orogen produced a greenschist-grade
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53 penetrative deformation along the Gondwana margin where the Ellsworth
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55 Mountains were within the linear belt between the Cape-Falklands and
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57 Pensacola Mountains. The Minaret Fm. carbonates in the Heritage range provide
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59 an opportunity to unravel the deformation using twinned calcite which is not
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4 present up section (i.e., the Crashsite, Whiteout or Polarstar Fms.) or along the
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6 orogenic strike. The twinned calcite preserves a layer-parallel shortening strain
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8 that is parallel to the Gondwanide thrust transport direction and consistent with
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10 the fold, cleavage and kinematic observations across the Ellsworth Mountains
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12 (Craddock et al. 1992; Sporli and Craddock, 1992a,b; Curtis, 1997, 1998, 2001) and
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14 twinning strains reported from the upper Gondwana section in the Cape belt
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16 (Craddock et al. 2007). Both limestones and vein calcite record a sub-vertical
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18 shortening strain (4 samples; see shortening axis stereonet inset in Fig. 12) that is
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20 also observed in orogenic belts with stacked nappes (Craddock and McKiernan,
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22 2007; Craddock et al. 2009). Breccia body formation, in 3 calcite stages, was
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24 contemporaneous with the peak Gondwanide orogen as cleaved Minaret Fm.
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26 limestone clasts are found in the breccias, vein calcite in the Minaret Fm. is often
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28 cleaved parallel to the range-wide penetrative cleavage, and breccia bodies are
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30 truncated by Gondwanaide orogeny thrusts (Fig. 8; Sporli et al. 1992; Craddock
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32 et al. 2008). Evidence of the Ordovician Ross orogen is not present. Breccia bodies
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34 are also truncated along the Dolence fault (Fig. 8) which has both reverse and
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36 sinistral kinematics and formed as a response to counterclockwise rotation of the
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38 Ellsworth-Whitmore terrane out of Gondwana in association with the intrusion
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40 of Jurassic granites into Grenville crust (Burgess et al. 2014; Craddock et al. 2016).
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42 Cretaceous uplift of 4 km (Fitzgerald and Stump, 1991) of the Sentinel Range is
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44 not well understood but the high elevation of the resistant Crashsite Group
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46 quartzites provided a buttress to ice motion in central Antarctica and stabilizes
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48 the ice cap. The tops of arêtes and horizontal glacial striations are at elevations of
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50 ~3000 m indicating the recent loss of ice volume (Denton et al. 1992).
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Conclusions

The Ellsworth basin had a robust supply of Pan African, Grenville and Archean zircons from the late Cambrian to the Permian where, in the basal Permian Polarstar Formation, Gondwanide orogen volcanic arc eudedral zircons fell into the basin (263 Ma; 258 and 262 Ma from Elliot et al. 2014). Our detrital zircon results support the presence of a Laurentian zircon source which may have been Laurentia (i.e., N. America) in the Cambrian and, perhaps, Laurentian crust in Coats Land (or undiscovered, nearby in Antarctica). The tectonic mechanism for initiating the rifting that formed the Ellsworth basin (and Kango, Kaaiman and Gomtoos inliers), while surrounded in space and time by tectonic convergence, remains unclear (Figure 11). Resolution of this problem could be addressed by a thorough detrital zircon study of the Heritage Group and other presumed Cambrian sediments around the EWT (Storey and MacDonald, 1987). The Ellsworth Mountains experienced a penetrative deformation throughout the 13,000 m section that is consistent with other parts of the Permian Gondwanide orogen. Rare carbonates in the Gondwana section, namely the Cambrian Minaret Fm., preserve a layer-parallel shortening strain that is parallel to Gondwanide thrust transport but also record a sub-vertical shortening overprint. Vertical shortening is consistent with thrust stacking and large, overturned folds (Fig. 9) also seen in the Cape belt. Magmatism in the Ellsworth Mountains part of the Ellsworth-Whitmore terrane is absent (Craddock et al. 2016) and Jurassic counterclockwise terrane rotation may be preserved by the small-offset oblique faults like the Dolence fault (Fig. 8).

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Figures

Fig. 1: Sub-ice topographic DEM of Antarctica (A) with continental crust terranes identified (EANT: East Antarctic craton; AP: Antarctic Peninsula; TI: Thurston Island; MBL: Marie Byrd Land; EWM: Ellsworth-Whitmore Mountains; from Dalziel, 2008) and in (B), a detailed sub-ice DEM of central west Antarctica. Red-orange areas are exposed above ice whereas yellow areas are sub-ice and blue areas are below sea level. The Ellsworth Mountains are the highest peaks and were uplifted by a SW-dipping series of thrusts faults. Inset C shows the relative position of the Ellsworth-Whitmore terrane in the Permian (Dalziel, 1997).

Fig. 2: A. Oblique aerial image of the Ellsworth Mountains looking ~north from the southern Heritage Range. Calcite strain sites are identified with stars (Fig. 5, Table 2). The Patriot Hills and Minaret Peak are identified in this image, and for reference in B, the shaded relief map of the Ellsworth Mountains, Antarctica showing the lower, southerly Heritage Range and the high peaks of the Sentinel Range. The Gondwanide thrust margin and transport direction is indicated (see Curtis, 1990). Detrital zircon samples sites are indicated (See Table 1, Figure 3). Samples 1,2 and 9 are from Flowerdew et al. (2007). A detailed geologic map of the range is found in Craddock et al. (1986).

Fig. 3: Stratigraphic column for the Ellsworth Mountains, Antarctica based on Webers et al. (1992) and Flowerdew et al. (2007). Radiometric ages are from Rees and Duebendorfer (1997), Rees et al. (1998) and Randall et al. (2000). Numbers in the column indicate detrital zircon samples from Figure 2 (see also Tables 1 and Appendix 2); samples 1, 2 and 9 are from Flowerdew et al. (2007). Calcite twinning strains are from the Minaret Pk. Fm. (Figure 5, Table 2).

Fig. 4: Summary relative probability plot for the Ellsworth Mountains, Antarctica including data from Flowerdew et al. (2007; open star symbol). Euhedral zircons (CL images above, with laser ablation holes) from the Polarstar Fm. produced a depositional age of 263 Ma. See Tables 1 and Appendix 2.

Fig. 5: Lower hemisphere projections of calcite twinning strain data (Table 2) for

the Minaret Fm. limestones and veins. Turner (1953) compression axes are contoured. Strain axes: e1=maximum shortening axis; e2= intermediate axis; e3= extension axis.

Fig. 6: Strike-slip faults cutting the Cambrian Minaret Fm., Heritage Range (A, B; mylonitic marble) with top-to-the-ENE kinematic indicators in Minaret mylonites (C) and Heritage Group volcanoclastics (D).

Fig. 7: (A) The “type” carbonate breccia body (~50 m high) in the southern Marble Hills of the Heritage Range. The vertical, cylindrical breccia body crosscuts an anticline-syncline pair and preserves a crude, sub-horizontal layering with clasts of cleaved Minaret Fm. marble. A second, horizontal breccia cylinder is present to the right. Breccia bodies crosscut each other (B) with younger breccias generally clast-poor and cleaved Minaret clasts are often serrated (C).

Fig. 8: (A) Carbonate breccia body hosted in Cambrian Minaret Fm. limestone truncated by a WSW-dipping thrust fault (top-to-the-northeast) and, (B) the Dolence fault (NW-SE strike) which juxtaposes folded Minaret Fm. limestones (that host breccia bodies) against Crashsite Group quartzites (see Fig. 2 for fault location). Sinistral motion kinematics are observed along the Dolence fault.

Fig. 9: Fold complexities in the Crashsite Group (Mt. Liptak and Landmark Peak Fms.) at high elevations in the Sentinel Range.

Fig. 10: Ternary diagram summarizing the detrital zircon data of the Elsworth Mts samples in terms of the three major geologically defined zircon age populations. The three apexes of the diagram represent a Pan-African zircon source end member (475-650 Ma), a Laurentian cratonic zircon source end member (1450-2000 Ma and 2500-3800 Ma) and a Grenville crust source end member (950-1350 Ma). The detrital zircon data of the samples in this study are normalized relative to these three age populations (projected on the ternary diagram) and define mixing assemblages between the Pan-African end member and an inferred Laurentian source that has approximately equal zircon-age proportions of Grenville crust and Laurentian craton. The error bars represent the statistical standard error of the proportions based on the sample size. For reference we plot the detrital zircon data from Cambro-Ordovician and Mesoproterozoic samples of the Laurentian Midcontinent region. The inset graph is a relative probability diagram of the Midcontinent Mesoproterozoic rift strata and Cambro-Ordovician arenites, illustrating the lack of zircon within the age range of ~2000-2500 Ma.

Fig. 11: The northern margin of Rodinia representing the final divergence of Laurentia and the early Cambrian amalgamation of proto-Gondwana (see Dalziel, 1991, 1997; Curtis, 2001 and Loewy et al. 2001). Stippled areas are Grenville crust, including the Ellsworth-Whitmore terrane, which is beginning to rift to accommodate deposition of ~7000 m of middle-upper Cambrian volcanoclastic sediment (Webers et al. 1992; Curtis, 1999).

Fig. 12: Schematic representation of the evolution of the Ellsworth-Whitmore terrane starting with rifting that led to the deposition of the Cambrian Heritage Group sediments, then the Cambrian-Permian Gondwana sedimentary sequence, all of which was deformed by the Gondwanide orogen. Intrusion of Jurassic granites followed as Gondwana diverged and the EWT rotated and uplifted to form the current high-standing mountain range.

Tables

Table 1: Detrital Zircon Sample Overview

Table 2: Calcite Twinning Strain Results

Appendices

1: U-Pb Dating and Calcite Twinning Strain Methods

2: 8 DZ data tables (spreadsheet).

Notes inserted below data Table 1:

1. Analyses with >10% uncertainty (1-sigma) in 206Pb/238U age are not included.
2. Analyses with >10% uncertainty (1-sigma) in 206Pb/207Pb age are not included, unless 206Pb/238U age is <500 Ma.
3. Best age is determined from 206Pb/238U age for analyses with 206Pb/238U age <900 Ma and from 206Pb/207Pb age for analyses with 206Pb/238U age > 900 Ma.
4. Concordance is based on 206Pb/238U age / 206Pb/207Pb age. Value is not reported for 206Pb/238U ages <500 Ma because of large uncertainty in 206Pb/207Pb age.
5. Analyses with 206Pb/238U age > 500 Ma and with >20% discordance (<80% concordance) are not included.
6. Analyses with 206Pb/238U age > 500 Ma and with >5% reverse discordance (<105% concordance) are not included.
7. All uncertainties are reported at the 1-sigma level, and include only measurement errors.
8. Systematic errors are as follows (at 2-sigma level): [sample 1: 2.5% (206Pb/238U) & 1.4% (206Pb/207Pb)] These values are reported on cells U1 and W1 of NUagecalc.
9. Analyses conducted by LA-MC-ICPMS, as described by Gehrels et al. (2008).
10. U concentration and U/Th are calibrated relative to Sri Lanka zircon standard and are accurate to ~20%.
11. Common Pb correction is from measured 204Pb with common Pb composition interpreted from Stacey and Kramers (1975).
12. Common Pb composition assigned uncertainties of 1.5 for 206Pb/204Pb, 0.3 for 207Pb/204Pb, and 2.0 for 208Pb/204Pb.
13. U/Pb and 206Pb/207Pb fractionation is calibrated relative to fragments of a large Sri Lanka zircon of 563.5 ± 3.2 Ma (2-sigma).
14. U decay constants and composition as follows: $^{238}\text{U} = 9.8485 \times 10^{-10}$, $^{235}\text{U} = 1.55125 \times 10^{-10}$, $^{238}\text{U}/^{235}\text{U} = 137.88$.
15. Weighted mean and concordia plots determined with Isoplot (Ludwig, 2008).

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Figure 1: Sub-ice topographic DEM of Antarctica (A) with continental crust terranes identified (EANT: East Antarctic craton; AP: Antarctic Peninsula; TI: Thurston Island; MBL: Marie Byrd Land; EWM: Ellsworth-Whitmore Mountains; from Dalziel, 2008) and in (B), a detailed sub-ice DEM of central west Antarctica. Red-orange areas are exposed above ice whereas yellow areas are sub-ice and blue areas are below sea level. The Ellsworth Mountains are the highest peaks and were uplifted by a SW-dipping series of thrusts faults. Inset C shows the relative position of the Ellsworth-Whitmore terrane in the Permian (Dalziel, 1997).

Figure 2: A. Oblique aerial image of the Ellsworth Mountains looking ~north from the southern Heritage Range. Calcite strain sites are identified with stars (Fig. 5, Table 2). The Patriot Hills and Minaret Peak are identified in this image, and for reference in B, the shaded relief map of the Ellsworth Mountains, Antarctica showing the lower, southerly Heritage Range and the high peaks of the Sentinel Range. The Gondwanide thrust margin and transport direction is indicated (see Curtis, 1990). Detrital zircon samples sites are indicated (See Table 1, Figure 3). Samples 1,2 and 9 are from Flowerdew et al. (2007). A detailed geologic map of the range is found in Craddock et al. (1986).

Figure

Figure 3: Stratigraphic column for the Ellsworth Mountains, Antarctica based on Webers et al. (1992) and Flowerdew et al. (2007). Radiometric ages are from Rees and Duebendorfer (1997), Rees et al. (1998) and Randall et al. (2000). Numbers in the column indicate detrital zircon samples from Figure 2 (see also Tables 1 and Appendix 2); samples 1, 2 and 9 are from Flowerdew et al. (2007). Calcite twinning strains are from the Minaret Pk. Fm. (Figure 5, Table 2).

Figure

Figure 4: Summary relative probability plot for the Ellsworth Mountains, Antarctica including data from Flowerdew et al. (2007; open star symbol). Euhedral zircons (CL images above, with laser ablation holes) from the Polarstar Fm. produced a depositional age of 263 Ma. See Tables 1 and Appendix 2.

Figure 5: Lower hemisphere projections of calcite twinning strain data (Table 2) for the Minaret Fm. limestones and veins. Turner (1953) compression axes are contoured. Strain axes: e1= maximum shortening axis; e2= intermediate axis; e3= extension axis.

Figure 6: Strike-slip faults cutting the Cambrian Minaret Fm., Heritage Range (A, B; mylonitic marble) with top-to-the-ENE kinematic indicators in Minaret mylonites (C) and Heritage Group volcaniclastics. (D).

Figure 7: (A) The “type” carbonate breccia body (~50 m high) in the southern Marble Hills of the Heritage Range. The vertical, cylindrical breccia body crosscuts an anticline-syncline pair and preserves a crude, sub-horizontal layering with clasts of cleaved Minaret Fm. marble. A second, horizontal breccia cylinder is present to the right. Breccia bodies crosscut each other (B) with younger breccias generally clast-poor and cleaved Minaret clasts are often serrated (C).

Figure 8: (A) Carbonate breccia body hosted in Cambrian Minaret Fm. limestone truncated by a WSW-dipping thrust fault (top-to-the-northeast) and, (B) the Dolence fault (NW-SE strike) which juxtaposes folded Minaret Fm. limestones (that host breccia bodies) against Crashsite Group quartzites (see Fig. 2 for fault location). Sinistral motion kinematics are observed along the Dolence fault.

Figure 9: Fold complexities in the Crashsite Group (Mt. Liptak and Landmark Peak Fms.) at high elevations in the Sentinel Range.

Figure

Figure 10: Ternary mixing plot of Ellsworth Mtns. detrital zircon data.

Figure

Figure 11: The northern margin of Rodinia representing the final convergence of Laurentia and the early Cambrian amalgamation of proto-Gondwana (see Dalziel, 1991, 1997; Curtis, 2001 and Leowy et al. 2011). Stippled areas are Grenville crust, including the Ellsworth-Whitmore terrane, which is beginning to rift to accommodate the deposition of ~7000 m of middle-upper Cambrian volcanoclastic sediment (Webers et al. 1992; Curtis et al. 1999).

Figure

Figure 12: Schematic representation of the evolution of the Ellsworth-Whitmore terrane starting with rifting that led to the deposition of the Cambrian Heritage Group sediments, then the Cambrian-Permian Gondwana sedimentary sequence, all of which was deformed by the Gondwanide orogen. Intrusion of Jurassic granites followed as Gondwana diverged and the EWT rotated and uplifted to form the current high-standing mountain range.

Table 1: Ellsworth Mountains Detrital Zircon Data

Sample	Rock Unit	Sample No.	Locality	Position	Elevation(m)	Zircons	Youngest Zircon	Oldest Zircon	Age
11	Polarstar Fm. (Lower Argillite)	OM-79-33	Match Ridge	77°34' 5.15S 86° 1'31.37W	2025	n=85	254 Ma	3163 Ma	Permian
10	Whiteout Conglomerate (Glacial Tillite)	OM-79-23H	Mt. Wyatt Earp	77° 35'23.47S 86° 18' 33.26W	2057	81	519	3569	Carboniferous
9	Crashsite Group# (Mt. Wyatt Earp Member)	R.6781.8A	Mt. Wyatt Earp	77°33' 22.77S 86°23' 39.99W	1893	44	379	2893	Middle Devonian
8	Crashsite Group (Mt. Liptak Fm.)	HAT	Vinson Massif	78°29.31S 85°44.70'W	4014	80	484	3024	Devonian
7	Crashsite Group (Landmark Peak Fm.)	HAS	Vinson Massif	78°33.62'S 86°04.18'W	2135	83	484	3540	Devonian
6	Crashsite Group (Landmark Peak Fm.)	HBD	Vinson Massif	78°31.29'S 85°39.78'W	4887	76	511	3158	Devonian
5	Crashsite Group (Landmark Peak Fm.)	HR-6	Bingham Peak	79° 30' 31.11S 84° 38' 33.67W	1394	83	505	1694	Devonian
4	Crashsite Group (Landmark Peak Fm.)	HBJ	E. Nimitz Glacier	78°42.59'S 85°42.54'W	1327	81	504	2032	Devonian
3	Crashsite Group (Mt. Twiss Member)	HR-37	Landmark Pk.	79° 7'16.02S 85° 25'28.24W	1398	82	486	3452	Devonian
2	Crashsite Group# (Mt. Twiss Member)	R.6758.4	Mt. Rossman	79° 46' 47.12S 82° 44' 25.24W	1430	47	493	3141	Cambro-Devonian
1	Heritage Group# (Fraser Ridge Fm.)	R.6208.2	Buggisch Peak	79° 49' 11.69S 83° 57' 19.55W	1440	33	518	2668	Upper Cambrian

n=775

(#-Data from Flowerdew et al. (2007)

Table 2: Calcite Twinning Strains, Heritage Range, Ellsworth Mountains, Antarctica

Sample	Rock Unit	Calcite Type/Age	Orientation	Grains (n=)	̸1	̸1(%)	̸2	̸2(%)	̸3	̸3(%)	NEV (%)	Ds (bars)	Fabric Interp.	Location
1	Minaret Limestone	LS/Cambrian	90°, 32°S	22	211°, 18°	-11.2	301°, 3°	2.2	36°, 88°	9	20	-357	LPS	Soholt Peaks
2v	Minaret Limestone	Vein/Cambrian	21°, 56°E	24	18°, 8°	-11.1	118°, 18°	3.4	308°, 84°	7.7	12	-423	VPS	Mt. Fordell
3	Minaret Limestone	LS/Cambrian	285°, 63°S	76	167°, 67°	-12.6	283°, 12°	4.1	14°, 11°	8.5	25	-326	LPS	Minaret Peak
3-NEV	Minaret Limestone	LS/Cambrian	285°, 63°S	19	52°, 36°	-3.1	318°, 6°	-0.2	219°, 53°	3.4	100	-421	LNS	Minaret Peak
4	Minaret Limestone	LS/Cambrian	290°, 40°S	71	251°, 31°	-12.5	168°, 4°	3.8	87°, 14°	8.7	28	-372	LPS	Mt. Fordell
4-NEV	Minaret Limestone	LS/Cambrian	290°, 40°S	20	95°, 27°	-6.9	274°, 5°	-1.3	183°, 31°	8.2	100	-457	LNS	Mt. Fordell
5	Minaret Limestone	LS/Cambrian	290°, 40°S	35	214°, 26°	-3.3	312°, 15°	0.5	117°, 52°	2.8	41	-412	LPS	Mt. Fordell
5-NEV	Minaret Limestone	LS/Cambrian	290°, 40°S	14	141°, 32°	-8.3	237°, 12°	2.2	357°, 84°	6.1	100	-532	LPS	Mt. Fordell
6	Minaret Limestone	LS/Cambrian	285°, 41°S	27	193°, 22°	-13.4	274°, 8°	-1.8	12°, 87°	15.2	18	-488	LPS	Minaret Peak
6v	Minaret Limestone	Vein/Cambrian	340°, 90°	38	18°, 11°	-4.3	277°, 12°	-0.6	169°, 41°	5.9	40	-531	VPS	Minaret Peak
6v-NEV	Minaret Limestone	Vein/Cambrian	340°, 90°	15	131°, 81°	-4.1	243°, 3°	0.2	334°, 8°	3.9	100	-502	VNS	Minaret Peak
7	Minaret Limestone	LS/Cambrian	298°, 44°S	37	157°, 38°	-6.3	79°, 21°	-1.3	312°, 52°	7.6	7	-458	LPS	Mt. Fordell
												Avg: -439		

LPS: Layer-parallel shortening; LNS: layer-normal shortening; VPS: vein-parallel shortening; VNS: vein-normal shortening.